Boosting Energy Efficiency of Heterogeneous Connected and Automated Vehicle (CAV) Fleets via Anticipative and Cooperative Vehicle Guidance

PI: Prof. Ardalan Vahidi

Clemson University (CU)

International Transportation Innovation Center (ITIC)

Argonne National Laboratory (ANL)

2018 DOE VTO Annual Merit Review

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Project ID EEMS029

Overview

Timeline

- Project start date:
  - Sep. 1, 2017
- Project end date:
  - Aug. 31, 2019
- Percent complete: 30%

Budget

- Total project funding
  - EERE: $1,159,987
  - FFRDC: $100,000
  - Cost share: $183,206
  - Total: $1,343,193
- Funding for Budget Period 1 (BP1):
  - $ 542,099 (EERE)+$50k (FFRDC)+109,853 (cost share)
- Funding for Budget Period 2 (BP2):
  - $517,888(EERE)+$50k (FFRDC)+$79,373 (cost share)

Barriers

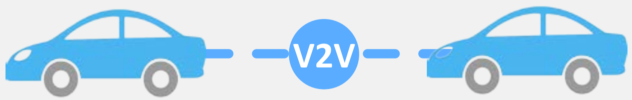
- Evaluating the network-wide energy efficiency gains of connected and automated vehicles.
- Real-time prototyping of energy efficient guidance algorithms.
- Accurately modeling and simulating mixed-traffic conditions consisting of autonomous and human-controlled vehicles.
- Real-time integration of experimental vehicles into large- scale traffic micro-simulations for more accurate energy use measurement.

Partners

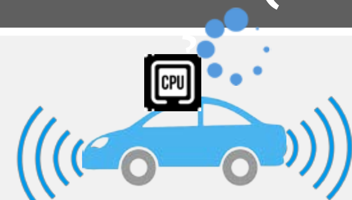
Relevance

CLEMSON UNIVERSITY

Connected and Automated Vehicles (CAVs)



By **Vehicle-to-vehicle (V2V) communication,** the event horizon of vehicles can be extended not only in time but also in space.



By **Autonomous Driving,** the incoming information can be processed effortlessly and the vehicle can be guided precisely.

Potential impact of CAVs in lowering energy use has received much less attention from the CAV research community.

Overall Objectives

- Propose **anticipative and collaborative guidance schemes** for CAVs to lower energy use.
- Obtain energy impacts for a mixed traffic fleet using simulations and experiments.

Objectives this period (Go/No-Go decision point)

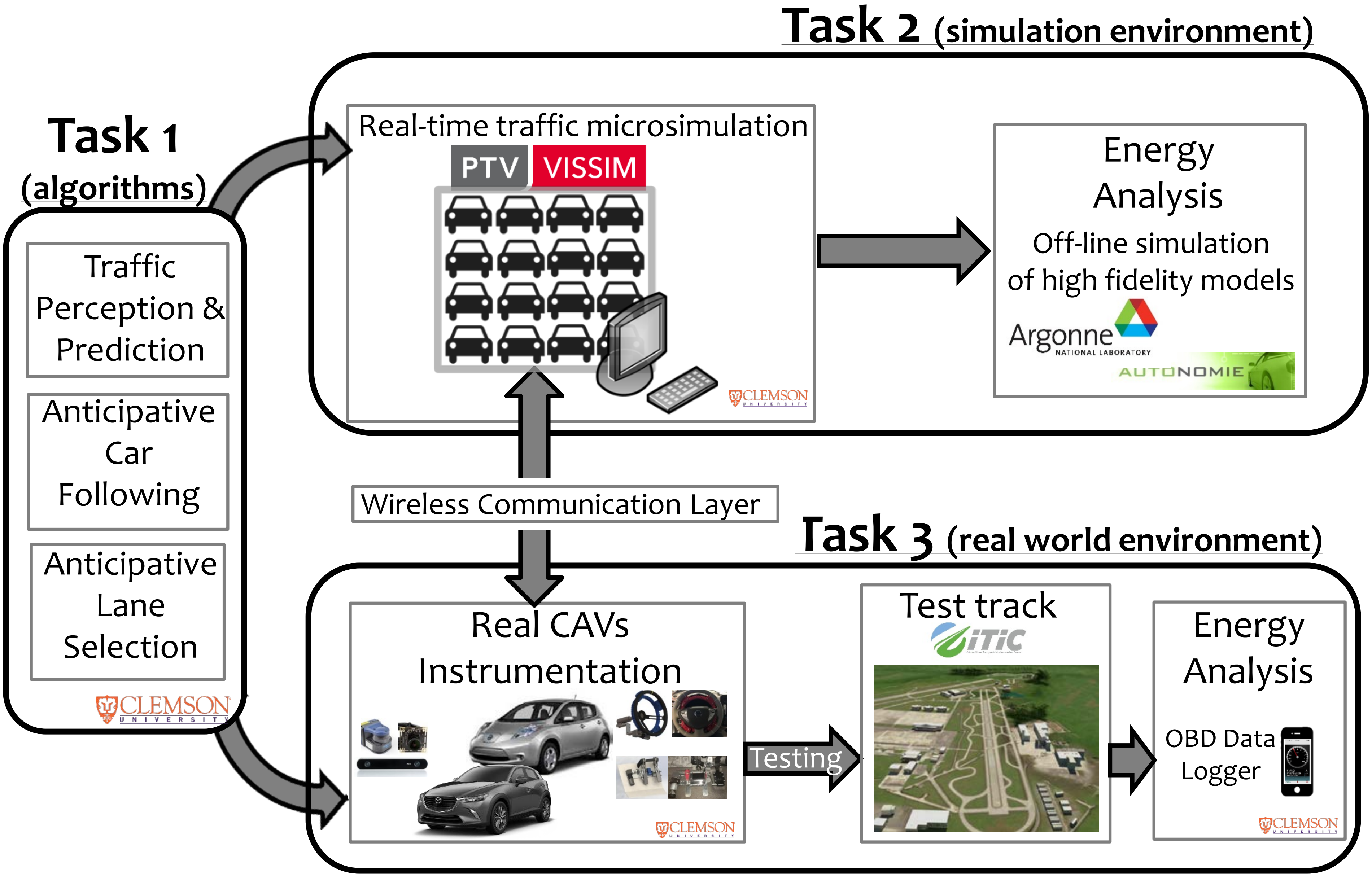
- up to 5% increase in energy efficiency for simulated CAVs using real-time implementable algorithms demonstrated in (Matlab) simulations.

Impact & Relevance to VT Office

- Potential of reducing abrupt maneuvers/slow downs and contributing to a **harmonized traffic flow.**
- Our findings could inform and shape new policies of VTO aimed at **accelerated deployment of CAVs to lower national energy consumption.**
- The VIL testing setup can find wider use across other VTO-funded initiatives.

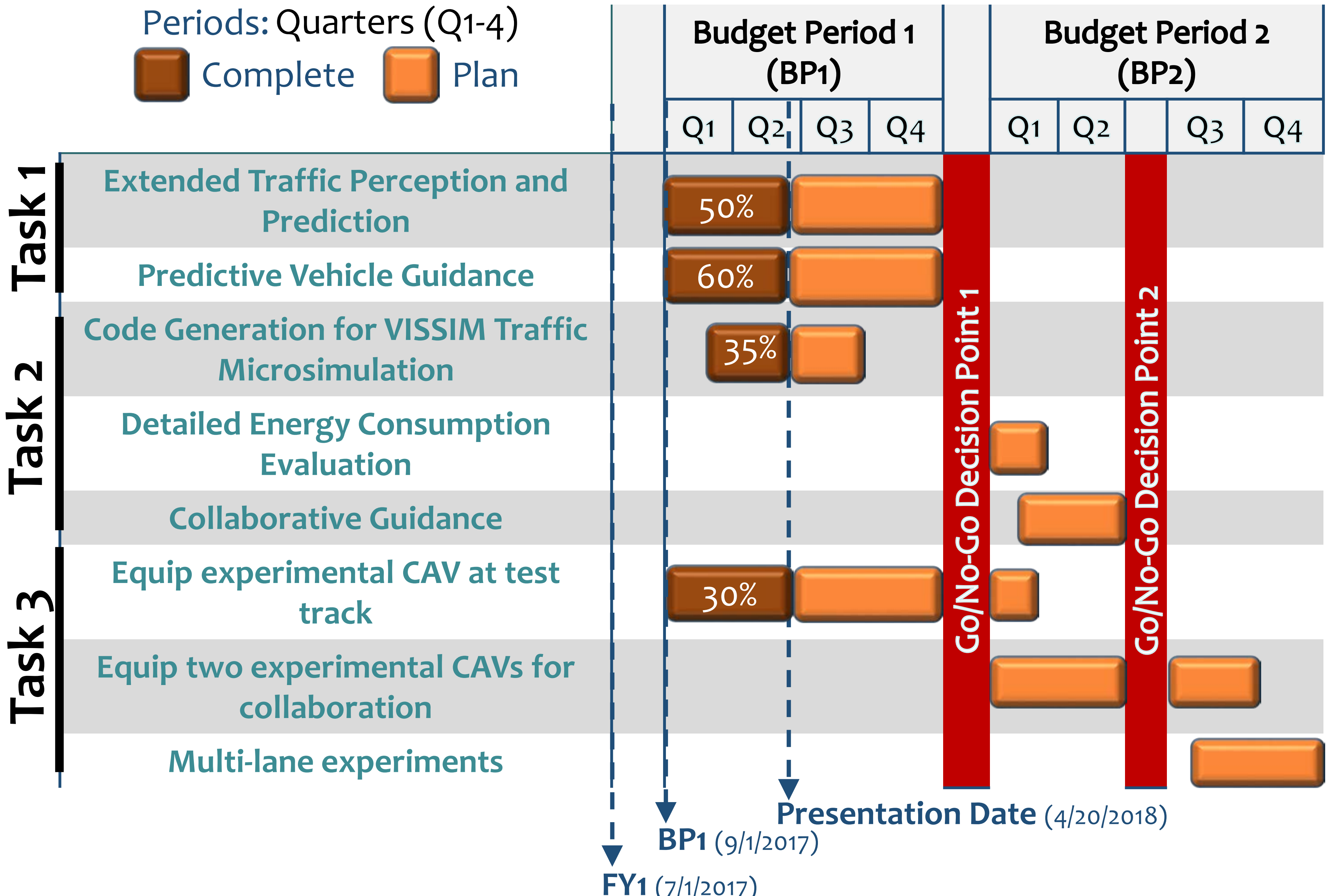
Our Approach

Project Overview



OBD: On-board diagnostics

Milestones



Periods: Quarters (Q1-4)
Complete
Plan
Budget Period 1 (BP1)
Budget Period 2 (BP2)
Q1 Q2 Q3 Q4
Q1 Q2 Q3 Q4
Task 1
Extended Traffic Perception and Prediction
50%
Predictive Vehicle Guidance
60%
Task 2
Code Generation for VISSIM Traffic Microsimulation
35%
Detailed Energy Consumption Evaluation
Collaborative Guidance
Task 3
Equip experimental CAV at test track
30%
Equip two experimental CAVs for collaboration
Multi-lane experiments
Go/No-Go Decision Point 1
Go/No-Go Decision Point 2
Presentation Date (4/20/2018)
BP1 (9/1/2017)
FY1 (7/1/2017)

Tasks Summary

Budget Period 1

Idea Generation

- Design the car-following and lane selection schemes
- Anticipation of neighboring vehicles' motion.
- Define controller objectives and constraints.

Preliminary Prototyping

- Implement a simulation system in Matlab.
- Rapidly test, revise, and prove the concept in an easily modified and debugged environment.
- Predict energy benefits using simplified models, and high fidelity models in Autonomie.

Real-time Implementation

- Collaborate to transfer a successful algorithm to C++.
- Validate using VISSIM and VIL testing.

VIL: Vehicle-in-the-loop

Task 1 Traffic Perception and Prediction

By anticipating the most likely motion of surrounding vehicles, we propose that our guidance algorithms performs better on average. For this reason we:

- Incorporate the extended perception schemes that fuse V2X information with those of on-board sensing by each CAV. This is used to construct the current state of surrounding traffic.
- Combine kinematic motion modeling and historical traffic data to create probabilistic prediction models for surrounding vehicles, traffic rules, customs, signals and signs.

Verification Using Real World Data

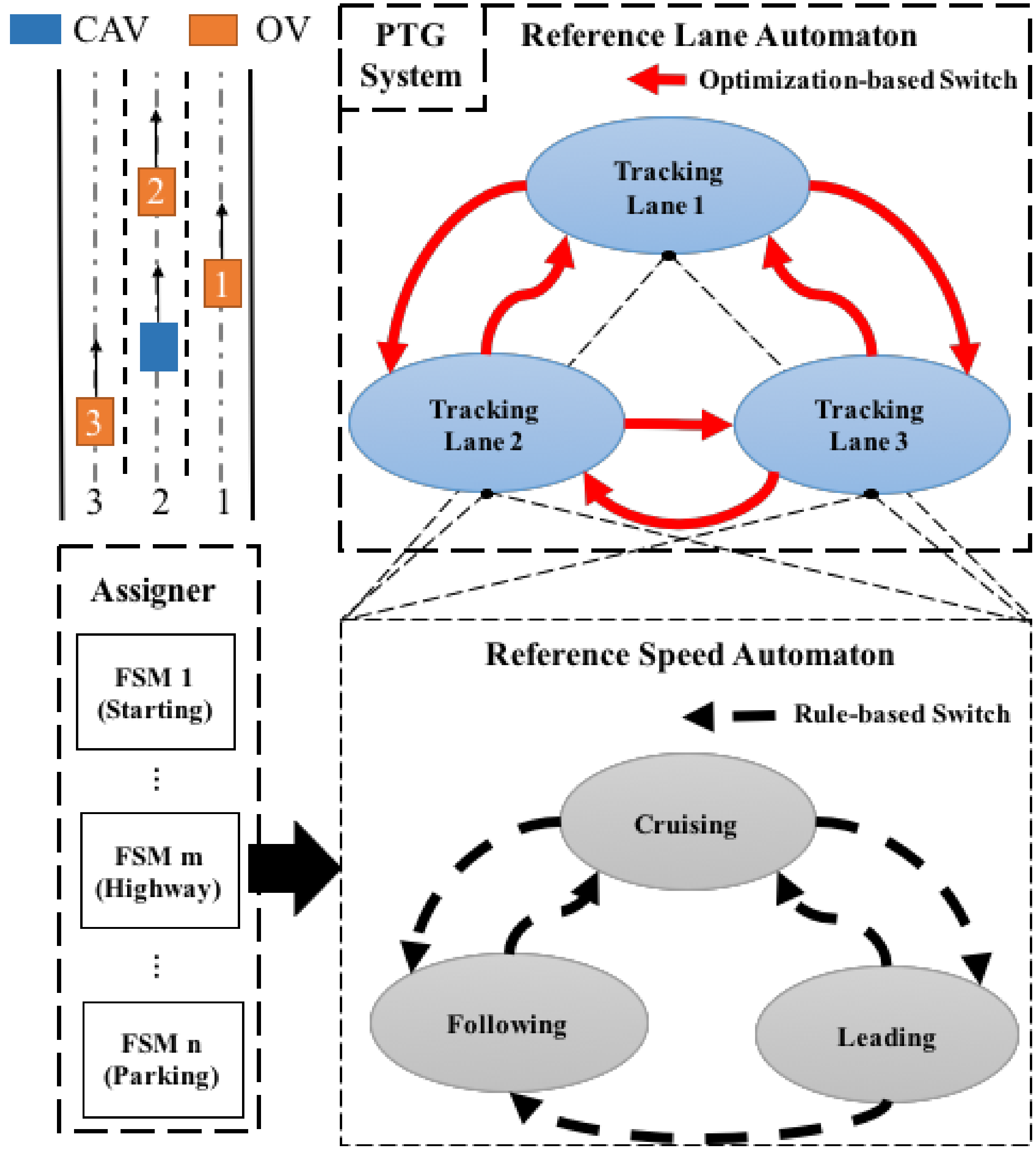
- We use high frequency real-time and historical data feed from a commuter bus route stretching 40 mile between two Clemson University campuses for verification of our proposed algorithms.

- Noting that each driver has a different driving style, we use each trip data to train a Markov chain predictor for individual drivers. Our proposed fusion algorithm predict the motion of each bus over every next 10 second future horizon.

Task 1 Anticipative Car-Following & Lane Selection

Establish a framework for Predictive Trajectory Guidance (PTG)

- Design constrained optimal control schemes to choose the best ego vehicle speed and lane to save energy and ensure safety in mixed-traffic conditions.



Task 2 Simulation Model Creation

Prototyping in Matlab

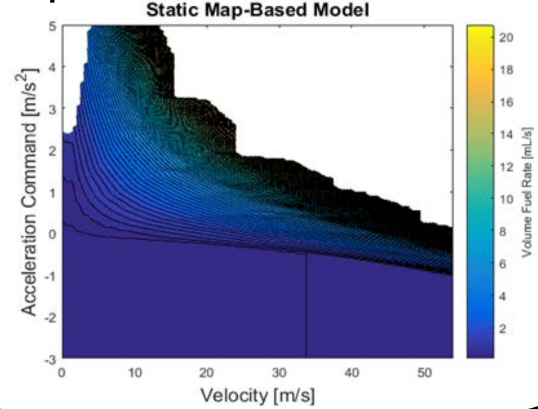
- Matlab enables rapid design iteration and calibration.
- A simplified powertrain model provides fast-running energy analysis.

Algorithm Design

Testing

Matlab
- *System Dynamics*
- *Controllers*

Simplified Powertrain Model

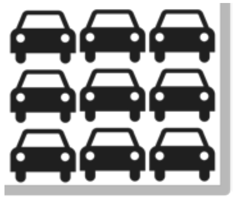


Micro-simulation in Vissim

- Successful design is then translated to a Dynamic Link Library (DLL) for integrated use with more complex scenarios in Vissim.
- DLL is more robust to wrap with parallel computing and embedded applications - as well as future products.

PTV VISSIM

Vissim
- *Road Topology*
- *Human Driver Behavior*
- *System Dynamics*

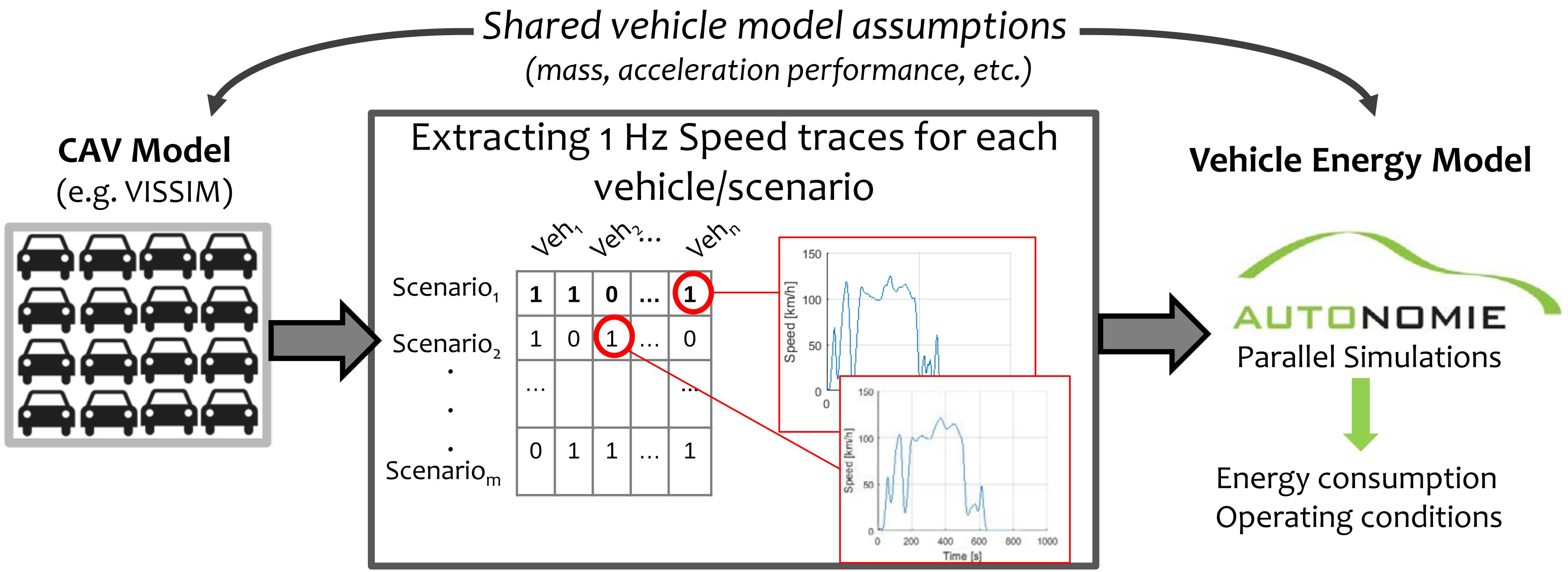


Control

DLL
- *Clemson Algorithm Implementation*

Task 2 Detailed Energy Consumption Evaluation

- Automated workflow loads CAV Simulation results (speed traces) and runs simulation using parallel computing in matter of few hours - scalable to 10^6 simulations.



- State-of-the-art Autonomie models used for energy consumption, incl.:
  - Multiple vehicle classes: light-duty cars to Class8 line-haul trucks
  - Advanced technologies: hybrids, EVs, high gear transmission, optimized engines, etc.
  - Multiple timeframes, current and future technologies (e.g. VTO targets)
- Leverages EEMS013 (Core Modeling) achievements.

Task 3 Vehicle-in-the-Loop Experimental Testbed

Vehicle instrumentation is to retrofit our two experimental vehicles (one electric and one combustion engine) with external sensors, actuators (motors) and controllers, and turn them into autonomous-driving-capable vehicles that are ready for the full-scale road test in this project.

Task 3 Breakdown

Budget Period 1		Budget Period 2	
Stage 1 Structural Design, Machining and Test	Stage 2 Individual Sensor Test and Controller Implementation	Stage 3 Single Vehicle Autonomous Driving Test	Stage 4 Multi-Vehicle Autonomous Driving Test
   			

Technical Accomplishments

and Progress

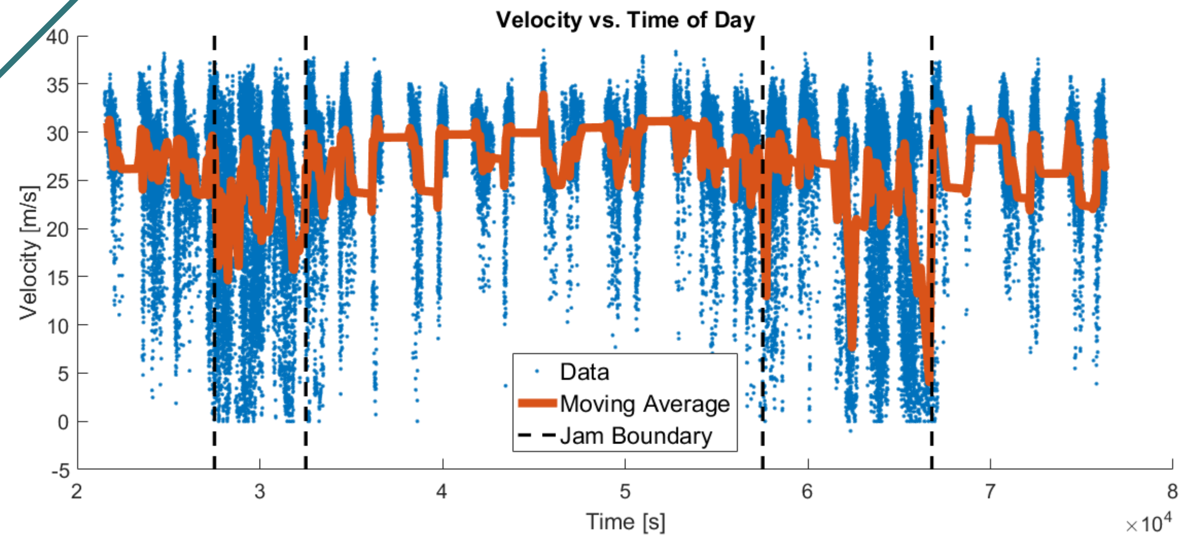
Accomplishments

Traffic Perception and Prediction

GPS data from **real Clemson University buses** in 2017 on I-85.

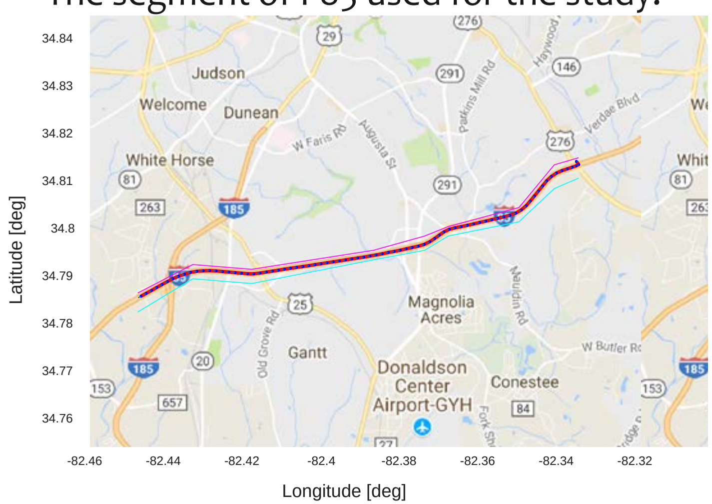
Position, time of day, velocity, velocity delta, and direction used to predict velocity using a **Markov chain.**

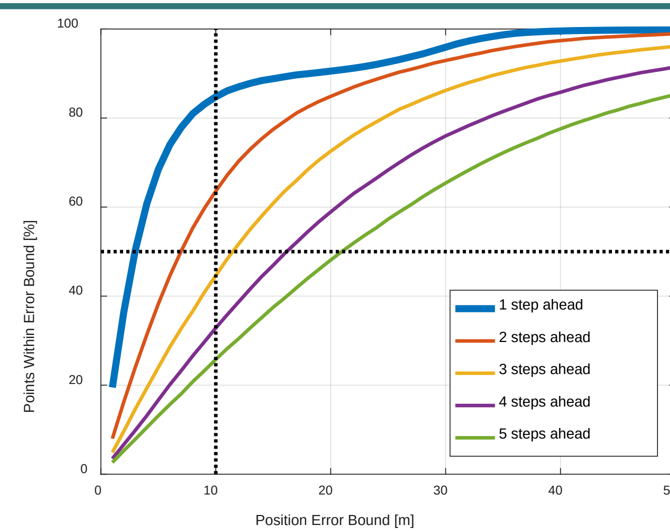
Position along roadway predicted **within 10 m, 5 s ahead, 85% of the time** (meets milestone).



Bus velocity vs. time of day in the GPS dataset. Slowdown-prone times are visible.

The segment of I-85 used for the study.



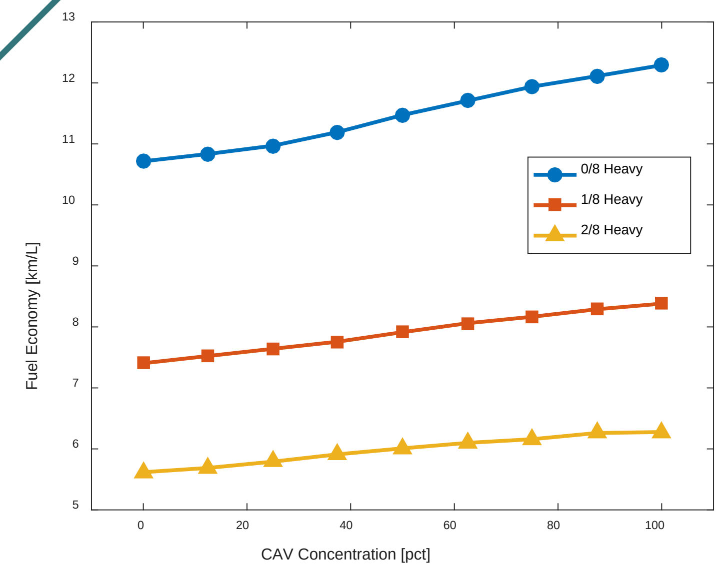


Markov chain position accuracy results.

Accomplishments
Anticipative Car Following scheme

Multi-agent microsimulations in Matlab show **1.3 to 1.6% fuel economy** improvement per **10% concentration of CAVs** running anticipative guidance.

Scenario (example below)
- Lead vehicle follows US06.
- An 8-vehicle string of following vehicles reacts to the speed disturbances.
- Class 8 heavy trucks are randomly positioned.
- Simulated human drivers sample parameters from distributions.
- 2224 random cases.



Fuel economy results from Matlab simulations with **Autonomie** energy analysis.

 CAV

 Conventional

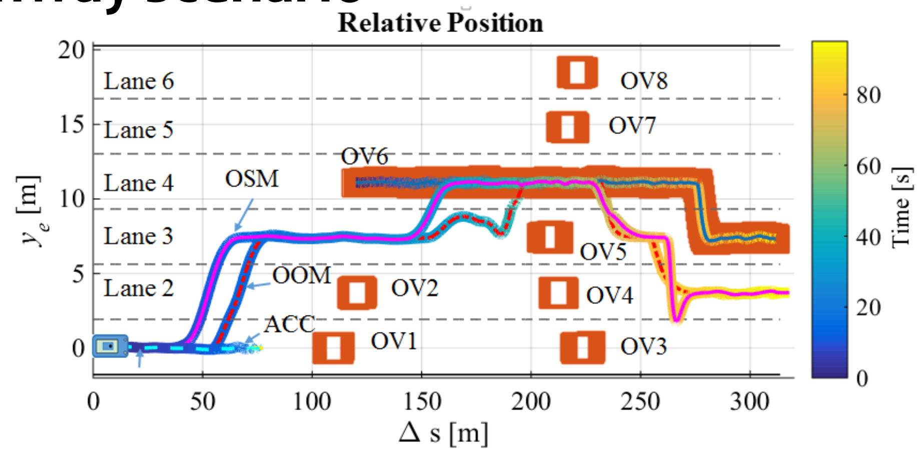
 Heavy (can be CAV or conv.)

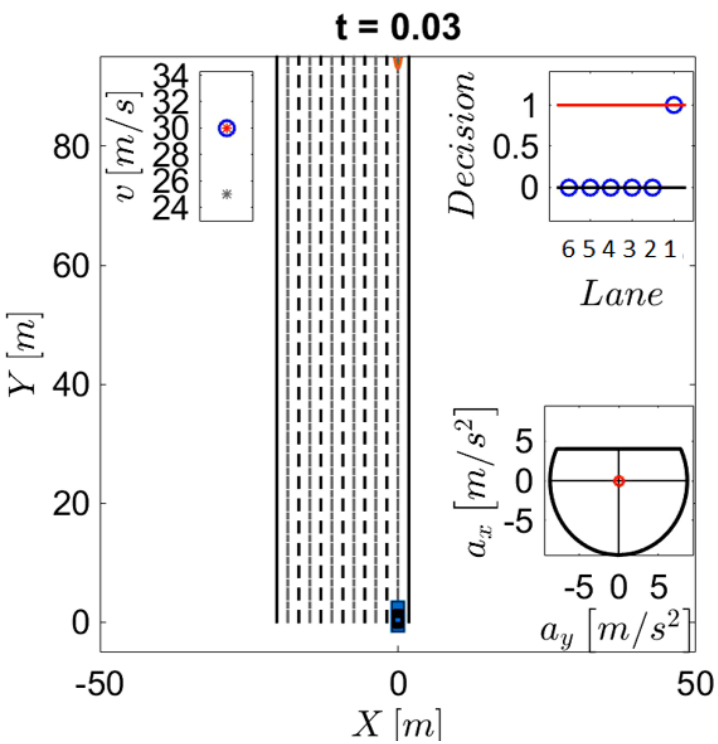
Example: 62.5% CAV Concentration, 2/8 Heavy

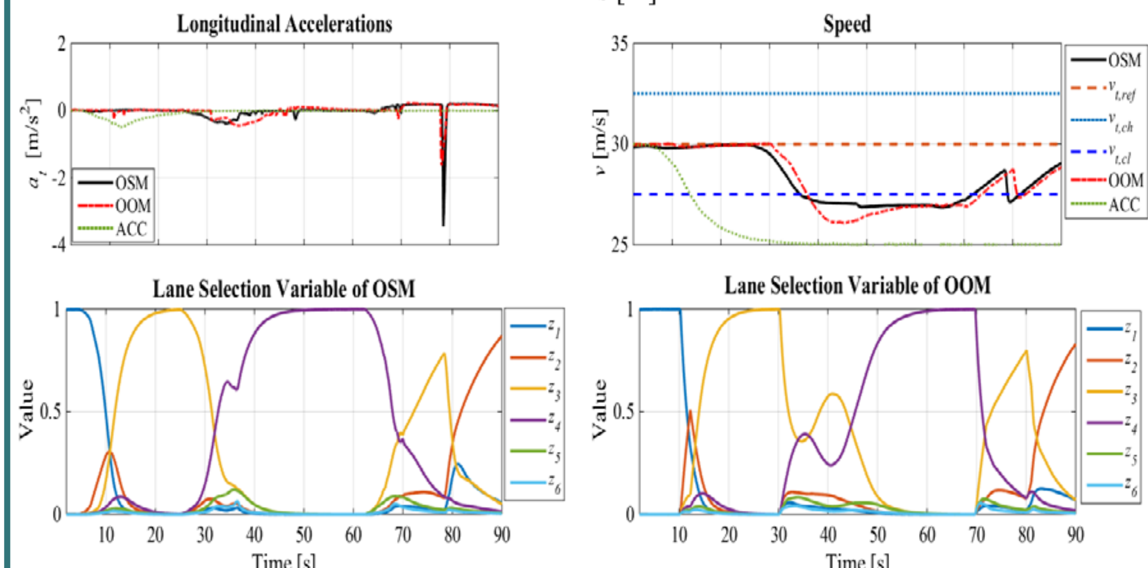
Publications
- Dollar, R. Austin, and Ardalan Vahidi. "Quantifying the impact of limited information and control robustness on connected automated platoons." In Intelligent Transportation Systems (ITSC), 2017 IEEE 20th International Conference on, pp. 1-7.
- Dollar, R. Austin, and Ardalan Vahidi. "Efficient and Collision-Free Anticipative Cruise Control in Randomly Mixed Strings." In review, IEEE Transactions on Intelligent Vehicles, 2017.

Simulated Example: A complex-highway scenario

- OOM: one optimized maneuver
  - Rule-based assignment on current state
- OSM: optimized sequence of maneuvers
  - Predictive maneuver planning with MPC
- ACC: adaptive cruise control







Publications

Q. Wang, B. Ayalew and T. Weiskircher (2018) "Predictive Maneuver Planning for an Autonomous Vehicle in Public Highway Traffic," IEEE Transaction on Intelligent Transportation Systems (Submitted, in review)

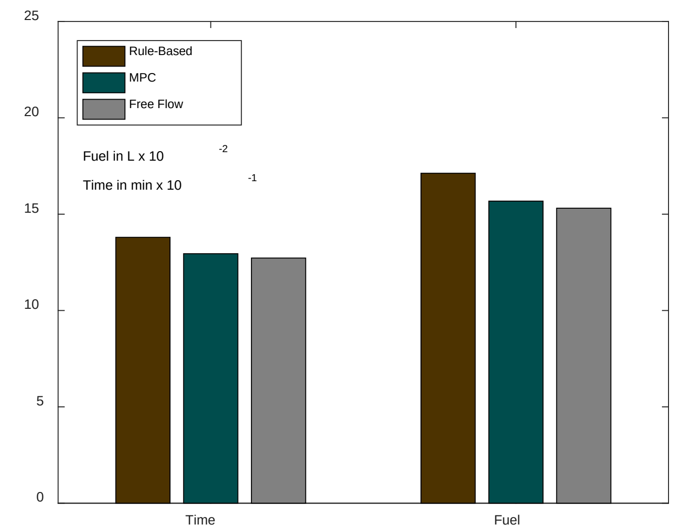
Accomplishments
Anticipative Lane Selection Scheme

Model predictive control using mixed integer quadratic programming changes lanes to smoothen longitudinal motion.

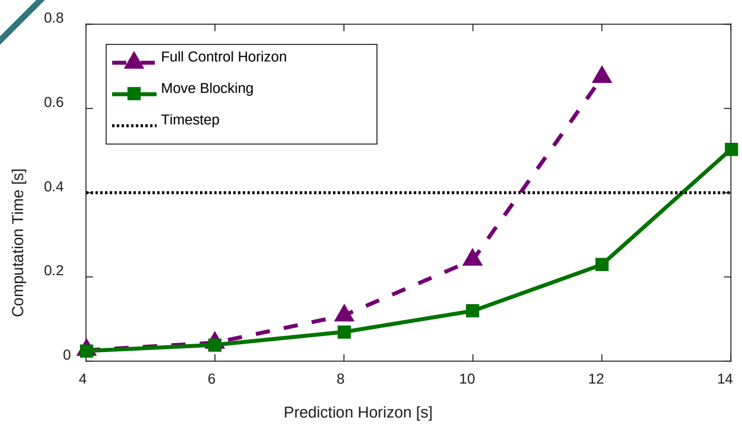
Preliminary microsimulations in Matlab show travel time and energy improvements in a 4-CAV **highway scenario** with **one lane impeded by a slow vehicle.**

- **Energy savings: 8.4%**
- **Time savings: 6.2%**
- ***Wasted* time and energy savings: ~80%.**

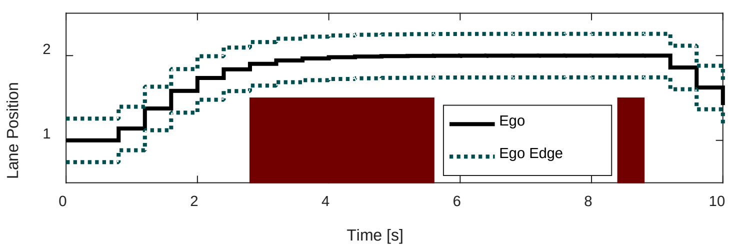
Computation time is a challenge, but trending to real-time feasibility (below).



Energy consumption and travel time results compared to reactive vehicles and constant-velocity travel.



Computation time increases with longer prediction horizons, but is reduced using move blocking.



Example of a planned trajectory to pass two vehicles. The obstructed region of (time, lane) space is in red.

Publication

Dollar, R. Austin, and Ardalan Vahidi. “Predictively Coordinated Vehicle Acceleration and Lane Selection Using Mixed Integer Programming." In review, ASME dynamic systems and control conference. American Society of Mechanical Engineers, 2018.

Accomplishments
Customized Traffic Microsimulation

- Test-track is modeled in Vissim
- Simulated vehicles **react** to other vehicles by either:
  - Vissim's probabilistic human driver models
  - Clemson designed MPC-based vehicle guidance

PTV VISSIM

<u>Vissim</u>
- *Road Topology*
- *Human Driver Behavior*
- *System Dynamics*

<u>DLL</u>

Custom Vehicle Guidance

Network Comm.

Vehicle Positions & Velocities

Google Protocol Buffer

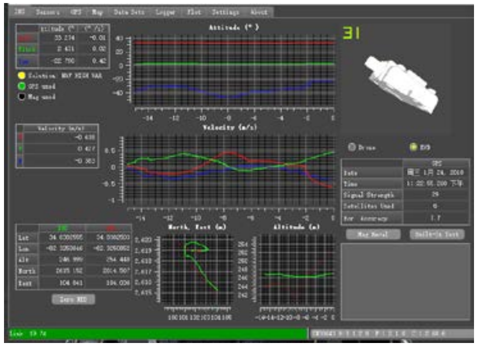
<u>Physical Vehicles</u>
- *On-board MPC*

VIL Only
- **Server-client connection** is established from the Vissim API to physical vehicles
- Data between simulated environment and physical environment is **virtually linked**

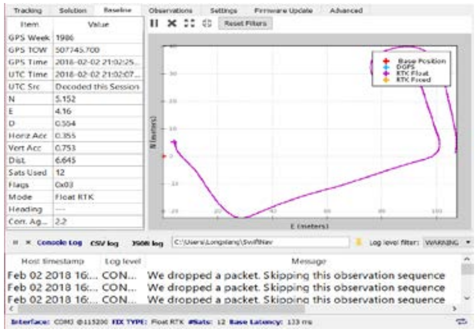
Accomplishments
Vehicle Instrumentation

Sensors
- Sensors needed for the controller have been tested separately. Sensors are sharing information through Robotic Operating System (ROS).

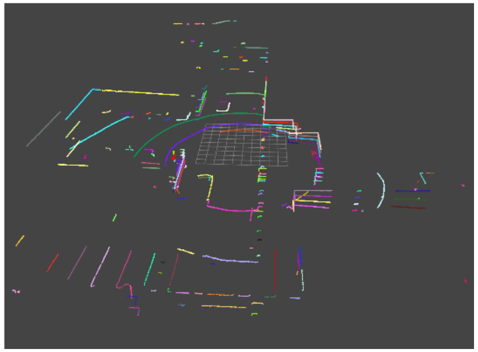
IMU
- Mounted on the central armrest in the vehicle.
- Performance is tested in vehicle. Can provide stable readings of vehicle attitudes around 3 axes, acceleration along 3 axes, and infer speed from integrated GPS antenna.
- Measurement will be used for vehicle motion control.



RTK-GPS
- Mounted on the roof of the vehicle
- Performance tested on vehicle. Can provide centimeter level positioning accuracy.
- Measurement will be used for vehicle localization.



Lidar
- Mounted on the roof of the vehicle
- Performance tested on vehicle. Can detect vehicle about 70 meters away.
- Data clustering algorithm implemented.
- Measurements will be used to prevent unexpected collision.



Actuator Structure Design and Implementation

- Structure design Implementation of the first vehicle is completed.
- Steering wheel is driven by a DC motor through a gear ring mounted behind it. Under emergency situation, the power of the motor will be cut off and the motor won't block the human driver's operation.
- Both brake and throttle pedals are controlled by a DC motor. The human driver can always push down the brake pedal and stop the car under emergency situations.
- Encoders mounted on motor shaft provide position and speed feedback.
- Both motors are controlled in the position mode.

Responses to Reviewers' Comments

This project was not reviewed last year

Collaboration and Coordination

Clemson University

	Task 1 (algorithms)	Task 2 (microsimulation)	Task 3 (experimental CAV)
PI and Co-PIs	Ardalan Vahidi, Beshah Ayalew	Ardalan Vahidi, Beshah Ayalew, D. Karbowski	Yunyi Jia, Ardalan Vahidi
Post-doctorals	Ali Reza Fayazi, G. G. Md. Nawaz Ali		
Grad. Students	R. Austin Dollar, Tyler Ard, Longxiang Guo, Nathan Goulet		

Argonne National Laboratory

Co-PI: Mr. Dominik Karbowski

To estimate energy efficiency using ANL's detailed powertrain simulation tool Autonomie.

International Transportation Innovation Center

Sub-contractor: Dr. Joachim G. Taiber

Responsible for the physical implementation of the communication network at the testbed, and to provide physical testbed access to perform the experiments.

PTV Group

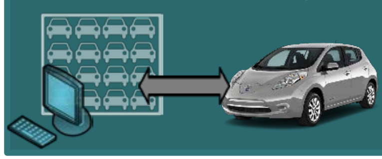
Provides the VISSIM traffic microsimulation tool, technical support, and traffic data.

Remaining Challenges and Barriers

Algorithms

- Accurate Anticipation of Road Events.
- Only few published results on the network-wide impact of trajectory guidance algorithms/technologies in mixed traffic.
- Extending our lane changing algorithm to mixed-traffic.
- On-board real-time computability & prototyping of the guidance algorithms to be developed.
- Real-time visualization of real vehicles in micro-simulations.

VIL Simulations

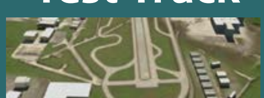


- Potential mismatch between simulation environment and reality.
- The VIL platform cannot be fully tested until our customized autonomous vehicle is functional.

CAV Instrumentation

- Retrofit the second vehicle and calibrate parameters for steering and pedal controls.
- Implement ego-vehicle motion control using onboard sensing
- Execute the proposed algorithms in real-time on dSPACE real-time control prototyping boards.
- Our implemented OBD data logger is only compatible with 29-bit CAN protocol (ISO 15765-4).

Test Track



- Risks such as wildlife crossing on the test track.
- The closed track is available for testing for limited days only.

Proposed Future Research

Upcoming Milestones:

- Collaborative Guidance.
- Detailed Energy Consumption Evaluation.
- Complete coding for the VISSIM microsimulation testbed.
- Equip Experimental CAVs at Test Track.
- Multi-Lane experiments.

Future work for FY18/19:

- Designing new collaborative guidance algorithms for CAVs aimed at reducing energy use of equipped vehicles.
- Estimating the energy efficiency impact via high fidelity models in collaboration with Argonne National Lab and their detailed powertrain simulation tool Autonomie.
- Demonstrating stable operation of VISSIM simulations at different penetrations of programmed CAVs and varying traffic demand volume.
- Implementing ego-vehicle motion control based on RTK GPS, IMU and Lidar sensing information.
- Completing a test track setup for Wi-Fi and DSRC communication between experimental and simulated vehicles.
- Demonstrating the energy savings via a novel vehicle-in-the-loop experimental testbed that allows co-simulation of hundreds of simulated vehicles and two experimental CAVs driven on a test track.
- Running multi-lane co-simulations and measure energy use of test vehicle when collaborating with simulated vehicles.
- Looking for solutions for insurance concerns to control the test track risks.

Any proposed future work is subject to change based on funding levels

Summary

Overall Objective

Propose anticipative and collaborative guidance schemes for CAVs, to achieve at least 10% gain in energy efficiency across a mixed traffic fleet with 30% penetration of CAVs.

Our Approach

- **Formulate a vehicle guidance scheme** that allows the CAVs to plan their energy optimal and safe future motion plan using the information obtained from our **Traffic Perception and Prediction algorithms**.
- To test the effectiveness of the proposed motion prediction scheme, we use **high frequency historical and real-time data** from Tiger Commute buses.
- To verify the energy efficiency benefit of the proposed vehicle guidance scheme, we use customized **traffic microsimulations.**
- To verify the energy efficiency benefit of the proposed vehicle guidance scheme in a near real-world condition, we use **test vehicles in a novel vehicle-in-the-loop co-simulation environment.**

Key Technical Accomplishments

- Multi-agent microsimulations in Matlab show anticipative car-following contributes to 1.3 to 1.6% fuel economy improvement per 10% concentration of CAVs.
- Position along roadway predicted within 10 m, 5 sec ahead, 85% of the time
- Preliminary microsimulations in Matlab show anticipative lane-change contributes to travel time and energy improvements in a 4-CAV highway scenario .
- Completed robotic autonomous driving system implemented in a Nissan Leaf.
- Completed IMU, RTK-GPS, and Lidar Installations on one test vehicle.

Key Milestone Accomplishments

- Demonstrated 50% success rate in anticipating the position of a target vehicle within a 10-meter radius of its actual position, 5 seconds in advance.
- Demonstrated 10% energy efficiency gain as a result of anticipative guidance in preliminary MATLAB micro-simulations and based on quasi-static fuel consumption maps.

Technical Back-Up Slides

Car Following Algorithm

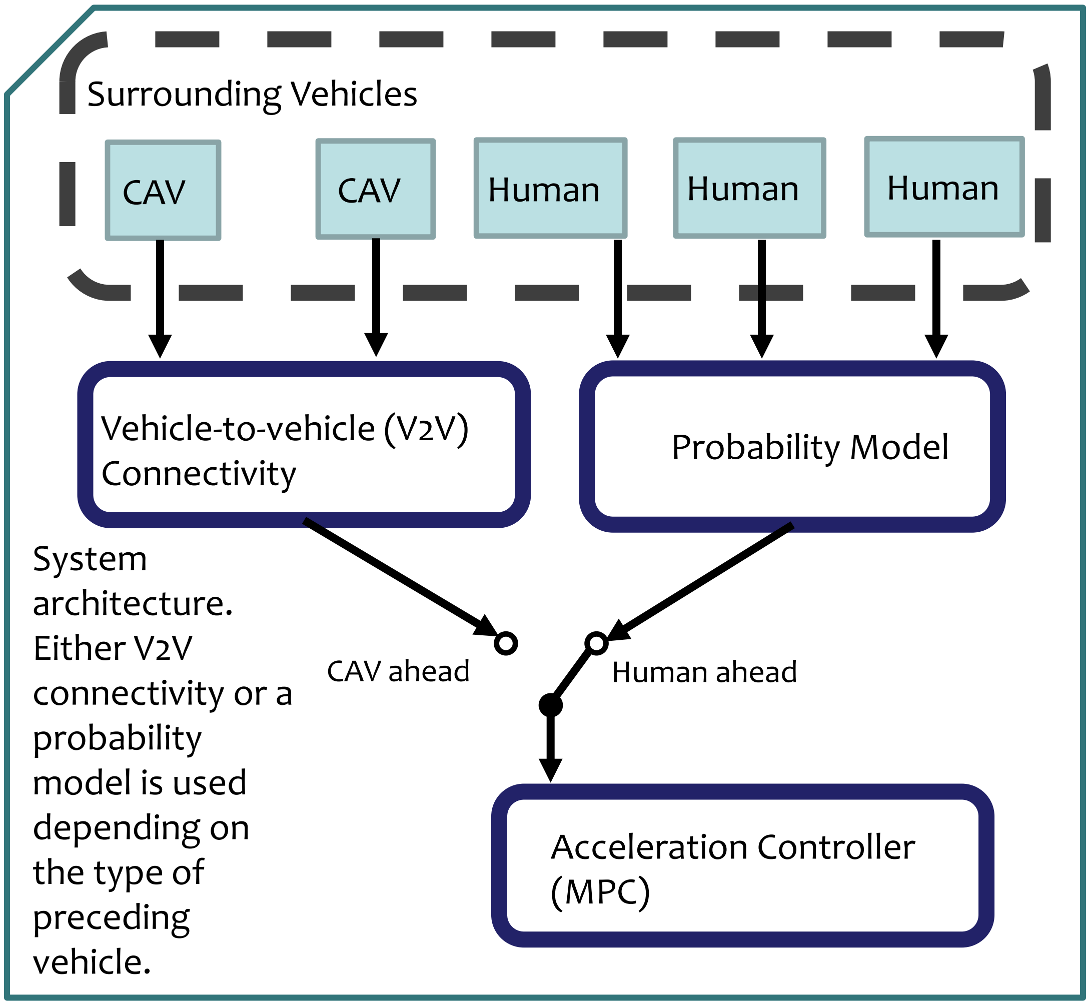
Model Predictive Control Formulation:

$$s_{ref} = r_{prob} - d_{ref}$$

$$\min_{u} J = q_g \left(s(N) - s_{ref}(N)\right)^2 + q_a a^2(N) + \sum_{i=0}^{N-1} \left[q_g \left(s(i) - s_{ref}(i)\right)^2 + q_a\left(a^2(i) + u^2(i)\right) \right]$$

$$\begin{aligned}
\text{s.t.} \quad & u_{min} \le u \le u_{max} \\
& 0 \le v \le v_{max} \\
& -m_1 v + u \le b_1 \\
& -m_2 v + u \le b_2 \\
& -m_1 v + a \le b_1 \\
& -m_2 v + a \le b_2 \\
& d_{min} \le r_{wc} - s \\
& -m_3 v(N) + s(N) \le \xi\left(r_{wc}(N) - d_{min}, v_{wc}(N)\right)
\end{aligned}$$

Terminal constraint for collision-free performance.



System architecture. Either V2V connectivity or a probability model is used depending on the type of preceding vehicle.

Lane Change Algorithm

MPC cost function

$$J = q_v\left(v(N) - v_{ref}(N)\right)^2 + q_a a^2(N) + q_l\left(l(N) - l_{ref}(N)\right)^2$$
$$+\sum_{i=0}^{N-1}\left[q_v\left(v(i) - v_{ref}(i)\right)^2 + q_a\left(u_1^2(i) + a^2(i)\right)\right.$$
$$\left. + q_l\left(\left(u_2(i) - l_{ref}(i)\right)^2 + \left(l(i) - l_{ref}(i)\right)^2\right)\right]$$

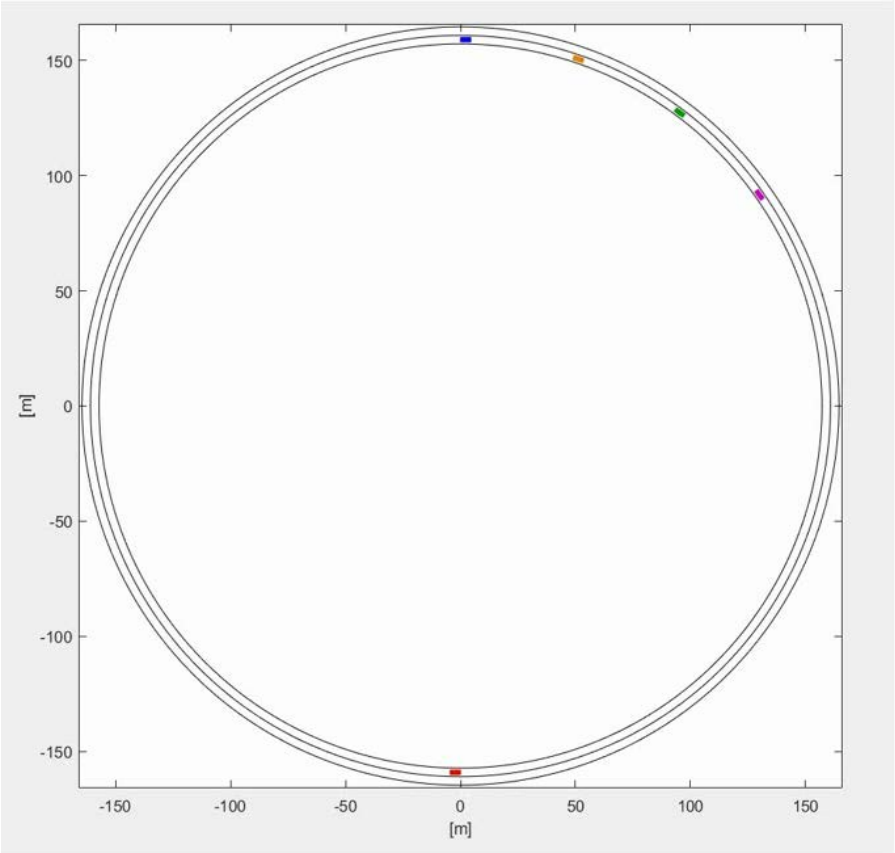
Set indicator variables for lane occupation:

Ex. (two lanes)

$$-l - M\mu_1 \leq -(2-\delta)$$
$$l + M\mu_1 \leq M + 2 - \delta$$
$$\mu_1, \mu_2 \in \{0, 1\}$$

Collision Avoidance

$$-s + M\beta_\zeta + M\mu_\lambda \leq 2M - s_{min}^{\lambda\zeta} + \varepsilon_1$$
$$s - M\beta_\zeta + M\mu_\lambda \leq s_{max}^{\lambda\zeta} + M + \varepsilon_1$$
$$\beta \in \{0, 1\}$$



Animation of an example simulation case. The red vehicle impedes traffic in the right lane and the CAVs, which have various desired velocities, must pass efficiently. Only vehicles close to the leader are shown.

Merging of Real Traffic and Simulation

Real-time visualization of traffic microsimulation mixed with a physical driver. Animation shows simulated vehicles reacting to physical vehicle.

Successful implementation of the **merging** of simulation environment and physical world into a **virtual reality** validates the VIL approach as a meaningful method for testing real autonomous vehicles in controlled environments. This provides a **basis for future CAV testing** that reaches beyond this project.